Influence of Stratospheric Circulation on the Predictability of the Tropospheric Northern Annular Mode

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Influence of stratospheric circulation on the predictability of the tropospheric Northern Hemisphere Annular Mode (NAM) in the boreal winter is examined using 5-year archive of 1-month ensemble forecast dataset provided by the Japan Meteorological Agency (JMA). It is found that the prediction skill of the 7-day averaged ensemble-mean NAM index in the upper troposphere is significantly improved for 5- to 13-day forecast when negatively large NAM indices are observed in the stratosphere around 30 hPa at the initial time of forecast in comparison with stratospheric positive NAM events. The regression analysis also supports the significant relationship between large prediction error of the upper tropospheric NAM index and stratospheric westerly anomalies. The asymmetric response of the forecast skill of the upper tropospheric NAM index to the polarity of the stratospheric NAM anomaly is also discussed in terms of the dependence of the upward propagation of planetary waves on stratospheric zonal wind anomalies.

1. Introduction

It is important to reveal the influence of the stratospheric circulation change on the predictability of the troposphere so as to improve the forecast skill of the extended-range prediction as well as the understanding of the stratosphere-troposphere dynamical coupling. The Northern Annular Mode (NAM) corresponding to the dominant hemispheric zonally-symmetric variability is a key to understand the stratospheric influence due to its downward migration properties [*Baldwin and Dunkerton*, 1999, 2001]. *Baldwin et al.* [2003] showed significant improvement of forecast skill of a statistical prediction for the surface NAM variability in mid-winter when the lowermost stratospheric NAM is used as the predictor instead of the surface NAM variability.

Recently, by conducting forecast experiments in the framework of the perfect model assumption [*Kalnay, 2003*], *Kuroda* [2008] showed a prolonged predictable period of tropospheric NAM variability up to 2 months for 2003/04 winter when large stratospheric NAM variability was observed. He also indicated that the predictable period was much limited (3 weeks) for 2002/03 winter when the NAM variation was weak. Although his study suggests the possible influence of the stratospheric variation on the predictability of the weather forecast, the perfect model experiment tends to overestimate the predictable period. In fact, the predictable period of the tropospheric NAM variability assessed by the operational 1-month ensemble forecasts of the Japan Meteorological Agency (JMA) is at most 6 days for 2002/03 winter [*Mukougawa and Hirooka*, 2007; hereafter referred to as MH07].

Hence, in this study, we will examine the dependence of the practical predictability of the tropospheric NAM variability on the stratospheric NAM anomaly. For this purpose, we analyze the 1-month (34-day) forecast data set of the JMA for 5 winter seasons from 2001/02 to 2005/06.

2. Data and Analysis Method

During the analysis period, the JMA 1-month ensemble predictions were carried out twice a week starting from 12 UTC every Wednesday and Thursday. Each ensemble prediction has 13 initial conditions. Here, the winter season is defined by a 4-month period from December to March, and we analyze forecasts starting from November 30 to February 28 (13 weeks for each winter). Hence, there are 26 ensemble forecasts in each winter. The 1-month predictions during this period were performed using a JMA global spectral model (JMA-GCM0103) with triangular 106 truncation (T106) and 40 vertical levels up to 0.4 hPa. For further model details, the reader should refer to MH07. The forecast data has been archived every 24 hr on a $2.5° \times 2.5°$ longitude-latitude grid at 22 levels from 1000 to 1 hPa. To verify the forecasts, JMA Global Analyses (GANAL) data set with 1.25-degree horizontal resolution at 23 levels from 1000 to 0.4 hPa is used.

We also used ERA-40 data set from November 1, 1957 to April 30, 2002 with 2.5-degree horizontal resolution at 23 pressure levels from 1000 to 1 hPa to define the NAM pattern by the following procedure as in MH07. First, we performed an EOF analysis to the monthly-mean height anomalies from November to April north of 20°N at each pressure level. Second, the regressed height anomaly to the corresponding 1st principal component is defined as the NAM pattern. Finally, the daily NAM index is obtained by projecting height anomaly on to the NAM pattern. Here, the anomaly is defined as a departure from daily climatology created by 60-day low-pass filtered daily-mean values at each calendar day. The positive (negative) NAM indices represent westerly (easterly) anomalies around 60°N.

To focus on the low-frequency variations of the NAM index, we will examine 7-day-running averaged ensemble-mean fields of the forecast in the following analysis. To construct 7-day running mean at day 0–3 prediction, GANAL data from day -3 to day -1 was used. The forecast skill is assessed using mean square error (MSE) and mean square spread (MSS) of the forecast at lead time t defined by

$$\mathrm{MSE} \equiv \frac{1}{N}\sum_{i=1}^{N}\left(\overline{e_i(t)}\right)^2, \tag{1}$$

$$\mathrm{MSS} \equiv \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(e(t)_i^j - \overline{e_i(t)}\right)^2, \tag{2}$$

respectively. Here, $e(t)_i^j$ is the forecast error of member j for the $i-th$ ensemble forecast, $\overline{e_i(t)}$ the ensemble-mean forecast error, M $(= 13)$ the number of member for each ensemble prediction, and N the number of the ensemble predictions ($N = 2 \times 13 \times 5 = 130$ for all ensemble predictions of the 5 winters from 2001/02 to 2005/06). Hereafter, MSE and MSS at each pressure level are normalized by the climatological variance of the NAM index for the 5 winters.

3. Results

3.1. Comparison between 2003/04 and 2004/05 Winter

At first, we will compare seasonal mean of the forecast error of the NAM index for the 2003/04 winter with the 2004/05 winter. As seen in Figures 1a, the 2003/04 winter is characterized by the prevailing downward migration of negative NAM anomalies from the upper stratosphere down to the surface. A major stratospheric sudden warming (SSW) took place in January 2004. On the other hand, the stratospheric circulation in the 2004/05 winter is characterized by positive NAM anomalies. Seasonally averaged [i.e., $N = 26$ in Eq.(1)] MSEs of the NAM index at each pressure level against the lead time are shown in Figures 1b and 1d. These two figures show that the prediction skill of the NAM index in the troposphere and stratosphere for the 2003/04 winter is better than the 2004/05 winter for the forecast period up to 30 days. For example, the 500-hPa MSE exceeds 0.5 (half the climatological variance of NAM index) for the forecast beyond 9-day lead time for the 2004/05 winter whereas it is smaller than 0.5 until 12-day forecast for the 2003/04 winter.

Thus, these results might suggest that the prediction error for the tropospheric NAM index becomes smaller when the negative NAM anomalies are observed in the stratosphere at the initial time of forecast. In the following, we will statistically examine the relevance of this suggestion using the 5 winter archive of the JMA 1-month forecast.

3.2. Classification by Stratospheric NAM

Firstly, we investigate the statistical significance of the difference in MSE and MSS between two groups with positively or negatively large initial NAM anomalies in the stratosphere. Figure 2a shows an example of dependence of MSE of the 250-hPa NAM index on the initial 30-hPa NAM index. The blue and red solid lines show MSEs of the forecasts for which initial 30-hPa NAM index is larger than 1 (climatological variance) and smaller than -1, respectively. Hereafter, the former (latter) is called as positive (negative) group. The number of the forecasts belonging to the positive and negative groups is 20 and 48, respectively. The black line is the averaged MSE for the other forecasts (normal group) of which number is 62. The statistical significance for the difference in MSE and MSS between the positive and negative groups at the lead time t in the following analysis is estimated by a procedure as in *Shiogama and Mukougawa* [2005] with 10000 resampled data. Figure 2a shows that the difference of MSE between the two groups is statistically significant at the 99% confidence level for the lead time between 5 and 13 days. In particular, the significance becomes higher than 99.9% for the lead time between 6 and 10 days. It should be also remarked that MSE of the normal group (black line) just lies between positive and negative ones for the lead times between 5 and 13 days, which implies almost linear relationship between MSE and 30-hPa NAM index. The broken lines in Figure 2a indicate squared magnitude of the mean error of the ensemble-mean prediction, $(\sum \overline{e_i(t)}/N)^2$, corresponding to the systematic error for each group. The systematic errors are much smaller than the MSEs, which indicates that the difference in MSE is not due to the model bias.

Figure 2b shows that the 30-hPa NAM anomaly also significantly affects MSE in the lower stratosphere and upper troposphere for the lead time around 8 days, and the longest interval of the lead time with significant difference around 8-day forecast is observed for the 250-hPa NAM prediction. However, the stratospheric NAM anomalies do not affect the predictability of the lower tropospheric NAM during this forecast period. We will focus on the forecast of the 250-hPa NAM index for the lead time around 8 days in the following analysis.

Secondly, we examine the pressure level of which NAM index most significantly affects the forecast skill of the 250-hPa NAM prediction. Figure 2c shows differences in MSE of the 250-hPa NAM index between the positive (NAM$\geq$1) and negative (NAM$\leq$-1) groups classified by the initial NAM index at each pressure level (the ordinate). For example, this figure shows that MSE of the 250-hPa NAM index for the negative group is significantly smaller than that for the positive group when the forecasts are classified by NAM anomalies above 200 hPa. In particular, the 30-hPa NAM index most significantly affects the 8-day forecast skill of the 250-hPa NAM index since the difference attains the highest statistical significance (99.997%). Figure 2c also shows that stratospheric NAM variations at upper pressure levels tend to influence the forecast skill of the 250-hPa NAM index for longer lead times. For example, the 5-hPa NAM variations produce the largest difference in MSE of the 250-hPa NAM index around 18-day forecast. It is also interesting to note that when mid-tropospheric NAM index has positively large values, the predictability of the 250-hPa NAM index for 10–23 day lead time tends to be enhanced.

Figure 3 shows the time evolution of mean square spread (MSS), defined by Eq.(2), of the 250-hPa NAM index for the positive and negative groups classified by the 30-hPa NAM index as in Figure 2a. The negative group has significantly smaller MSS than the positive group at 99.9% confidence from 5-day to 19-day forecast. Hence, it is suggested that the MSE dependence on the stratospheric NAM index is not to due to the model bias, but results from influence of the stratospheric NAM anomalies on the dynamical stability of the tropospheric NAM mode. In fact, the observed 250-hPa NAM variance among the positive group (blue broken line) is larger than that for the negative group (red broken line) after 2 days from the initial time in accordance with the significant difference in MSS between the two groups.

3.3. Regression Analysis of Tropospheric NAM Error

We also made a regression analysis with respect to MSE of the 250-hPa NAM index using all ensemble predictions [$N = 130$ in Eq.(1)]. Figure 4 shows regressed zonal-mean zonal wind and E-P flux of zonal wavenumber 1 (WN1) at the initial time of forecast. The statistical significance is assessed by the Student's $t-test$. Figure 4a indicates that larger MSE of 250-hPa NAM index for 12-day prediction is related to westerly anomalies in the upper stratosphere in mid-latitudes. For 8-day NAM prediction, the related westerly anomalies extend downward to the lower stratosphere around 50°N (Figure 4b), which suddenly disappears for forecasts shorter than 4 days (Figure 4c). The correlated stratospheric westerly anomaly and its downward extension are also confirmed from Figure 2.

Figure 4 also gives us an plausible explanation for the downward extension of the correlated westerly anomaly. The regressed WN1 E-P flux vectors indicate that larger MSE of the 250-hPa NAM index is associated with downward and equatorward propagation of anomalous WN1 wave activity in the lower stratosphere and upper troposphere. The WN2 component also has less significant E-P flux anomalies in the stratosphere (not shown). The accompanied anomalous E-P flux divergence of both components in the lower stratosphere (not shown) will extend the westerly anomaly downward.

4. Concluding Remarks

In order to examine the influence of the stratospheric circulation on the predictability of tropospheric large-scale motions in the boreal winter, we made a statistical analysis using 5-winter archive of 1-month ensemble forecast data set from 2001/02 to 2005/06 provided by the JMA. In particular, we investigated dependence of the predictability of the tropospheric Northern Annular Mode (NAM) index on the polarity of the stratospheric NAM anomalies at the initial time of forecast.

It is found that the stratospheric NAM anomalies around 30 hPa most significantly affect the predictability of a 7-day averaged ensemble-mean NAM index in the upper troposphere. The mean square error (MSE) of the forecasts with negatively large 30-hPa NAM anomalies at the initial time is significantly smaller than that of the forecasts with positively large NAM anomalies for the lead time from 5 to 13 days. Moreover, the pressure level of which NAM anomaly most significantly affects the forecast skill of the 250-hPa NAM index tends to shift downward to the lower stratosphere for shorter lead times. However, the stratospheric and tropospheric NAM anomalies do not affect the predictability of lower tropospheric NAM index.

Regression analyses with respect to MSE of the 250-hPa NAM index also confirm the above results. The suppressed upward propagation of WN1 planetary waves in the stratosphere and their enhanced equatorward propagation in the upper troposphere are also significantly related to MSE of the 250-hPa NAM index. It is also interesting to note that in the analysis period from 2001/02 to 2005/06 winter, there were 5 major SSWs which are roughly classified as the vortex displacement type associated with the amplification of WN1 component. This might be related to the important role of WN1 component for the downward shift of the regressed stratospheric westerly anomalies.

Our results are also consistent with *Kuroda* [2008] which remarked very high predictability of the tropospheric circulation just before the occurrence of a major SSW, corresponding to a negatively large NAM event. He argued the high predictability in connection with the magnitude of stratospheric circulation anomalies. However, our study insists the primarily importance of the polarity of the stratospheric NAM anomalies for the predictability of the tropospheric circulation. To reveal which aspect of the stratospheric circulation anomalies is much more relevant to the tropospheric predictability, we have to conduct a series of ensemble reforecast experiments from several initial conditions with a variety of magnitude and polarity of stratospheric NAM anomalies for a further study.

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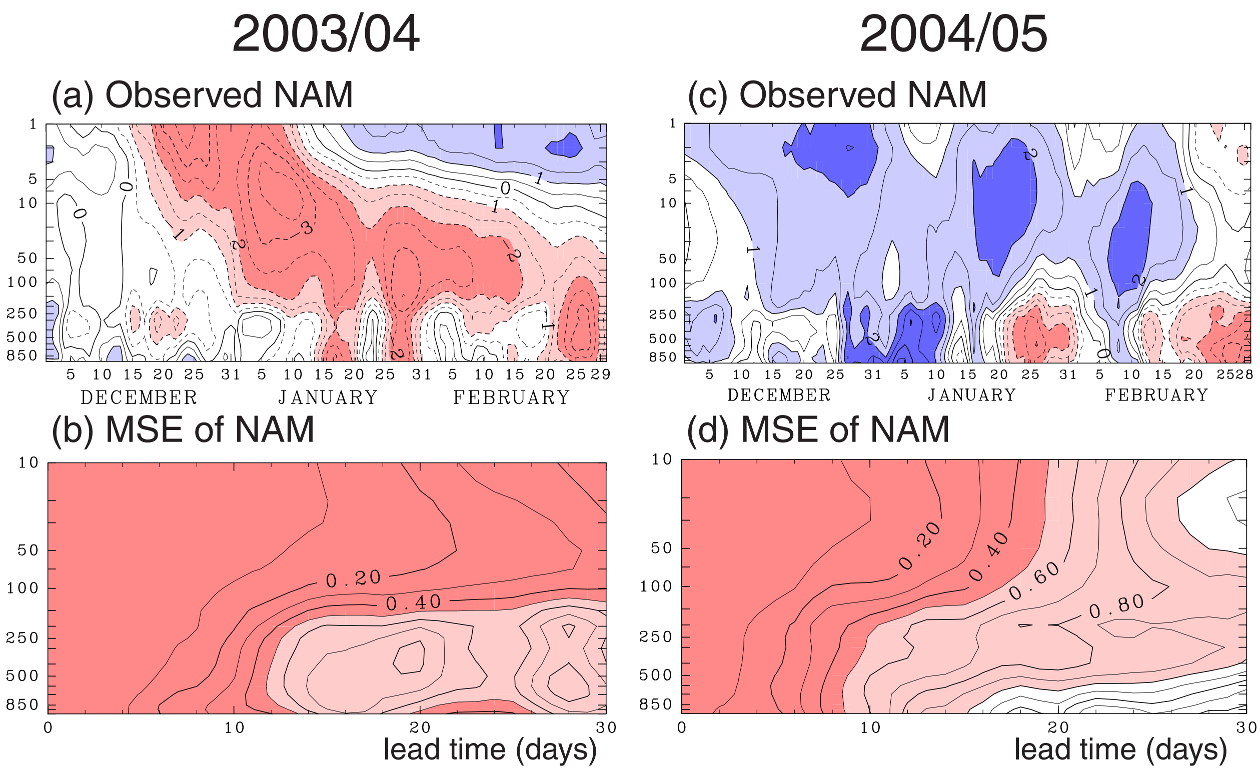
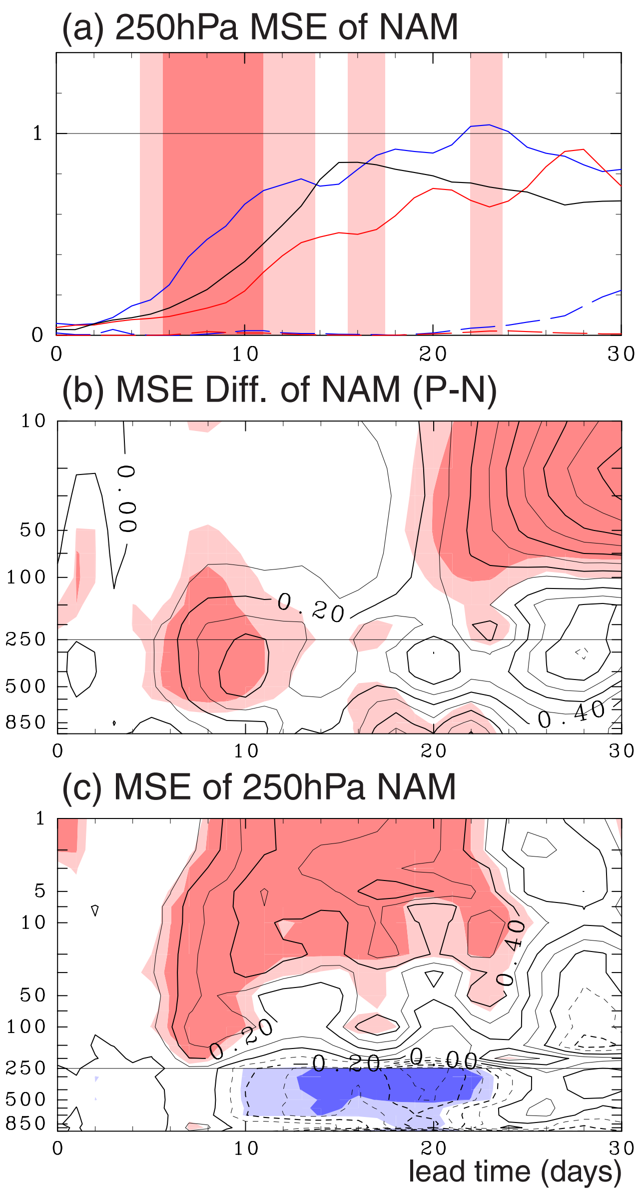
Figure 1. (a) Time variation of observed NAM index at each pressure level for 2003/04 winter. (b) MSE of the NAM index at each pressure level for 2003/04 winter. The absicca is the lead time in days. The values less than 0.5 (1.0) are heavily (lightly) shaded. The right panels are the same as the left ones except for 2004/05 winter.

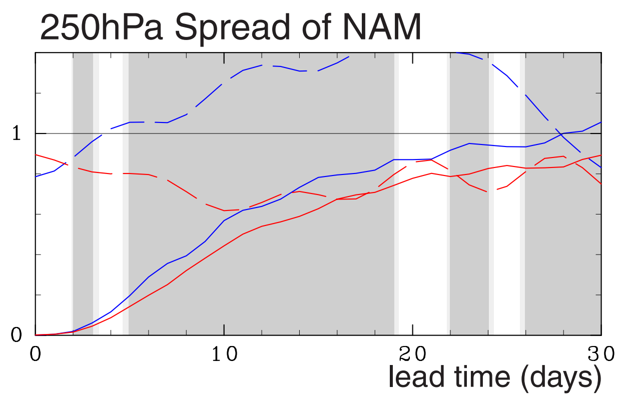
Figure 2. (a) Time evolution of MSE of the NAM index for the forecasts classified by the initial 30-hPa NAM index against the lead time (solid lines). Broken lines are the squared magnitude of the mean error of the ensemble-mean forecast. Blue (red) lines are for the positive (negative) group. Time intervals of the lead time when the difference in MSE of the NAM index between the two groups is significant at 99.9 (99)% confidence are heavily (lightly) shaded. The black line shows MSE for the normal group. (b) Difference in MSE at each pressure level between the two groups classified by the initial 30-hPa NAM. (c) Difference in MSE of the 250-hPa NAM index between the two groups classified by initial NAM index at each pressure level (the ordinate). Positive values in (b) and (c) indicate larger MSE for the positive group. The absicca is the lead time in days, and statistically significant regions are shaded as in (a).

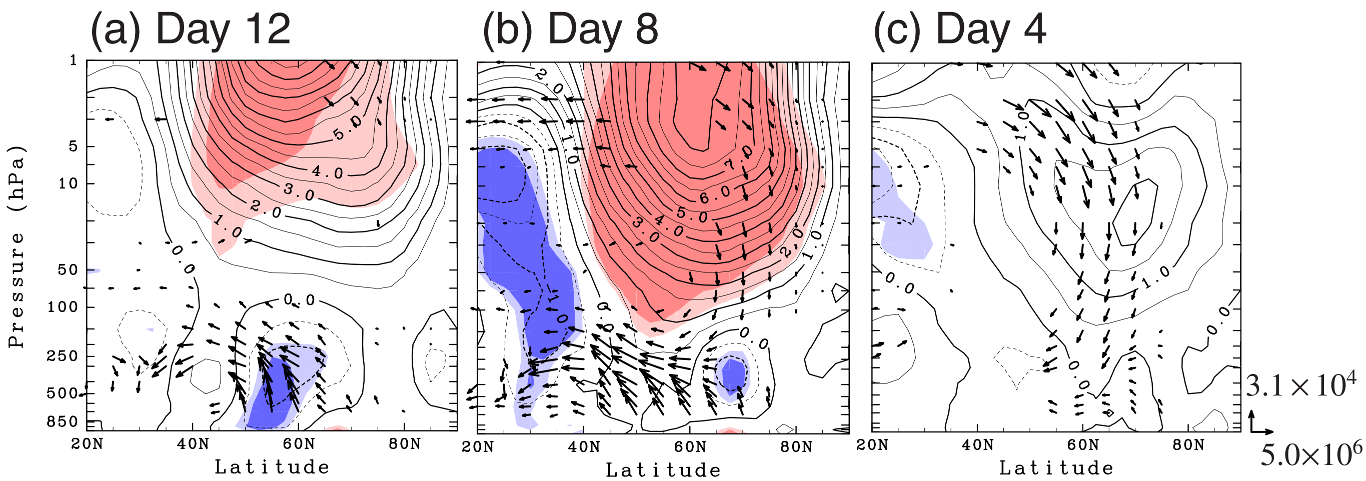
Figure 3. As in Figure 2a except for MSS of the NAM index. Time intervals when the difference in MSS between the two groups is significant at 99.9 (99)% confidence are heavily (lightly) shaded. Broken lines show the variance of 7-day averaged observed NAM index from the initial time for each group. Blue (red) lines are for the positive (negative) group.

Figure 4. Regressed anomalies of zonal-mean zonal wind (contours: m s^{-1}) at the initial time of forecast on MSE of the 250-hPa NAM index for (a) 12-day, (b) 8-day, and (c) 4-day forecasts. Regions are heavily (lightly) shaded where correlation coefficients are significant at 99 (95)% confidence. The vectors indicate the regressed WN1 E-P flux anomalies (Kg s^{-2}) of which vertical or horizontal components are significant at the 90% level, and the magnitude of the vector is scaled by the reciprocal square root of the pressure.


2003/04
2004/05
(a) Observed NAM
(c) Observed NAM
DECEMBER
JANUARY
FEBRUARY
(b) MSE of NAM
(d) MSE of NAM
0.20
0.40
0.60
0.80
lead time (days)
lead time (days)


(a) 250hPa MSE of NAM
1
0
0
10
20
30
(b) MSE Diff. of NAM (P-N)
10
50
100
250
500
850
0.00
0.20
0.40
0
10
20
30
(c) MSE of 250hPa NAM
1
5
10
50
100
250
500
850
0.20
0.40
0.20
0.00
0
10
20
30
lead time (days)


250hPa Spread of NAM
1
0
0
10
20
30
lead time (days)


(a) Day 12
(b) Day 8
(c) Day 4
Pressure (hPa)
Latitude
20N
40N
60N
80N
1
5
10
50
100
250
500
850
3.1×10^4
5.0×10^6